Spacecraft Mass Trade-Offs Versus Radio-Frequency Power and Antenna Size at 8 GHz and 32 GHz

C. E. Gilchriest
Telecommunications Systems Section

The purpose of this analysis is to help determine the relative merits of 32 GHz over 8 GHz for future deep space communications. This analysis is only a piece of the overall analysis and only considers the downlink communication mass, power, and size comparisons for 32 GHz and 8 GHz. Both parabolic antennas and flat-plate arrays are considered. The Mars Sample Return mission is considered in some detail as an example of the trade-offs involved; for this mission the mass, power, and size show a definite advantage of roughly 2:1 in using the 32 GHz over 8 GHz.

I. Introduction

The purpose of this analysis is to help determine the relative merits of 32 GHz over 8 GHz for future deep space communications. This analysis is only a piece of the overall analysis and only considers the downlink communication mass, power, and size comparisons for 32 GHz and 8 GHz.

A mission set is selected to demonstrate the 32 GHz versus 8 GHz relative merits. This set includes Saturn Orbiter Titan Probe (SOTP) and Mars Sample Return (MSR). While the following analysis applies to either (or any mission for that matter), it is tailored to the MSR where the size and mass of the antenna are important parameters because of the possible wind drag and vehicle upset, high center of gravity and vehicle upset, and compounding of the mass problems with cascaded vehicles. The launch-vehicle envelope with respect to the antenna size is another important parameter.

Certain improvements over 1985 performance levels are assumed for the ground stations for both 8 GHz and 32 GHz and are discussed elsewhere [1]. Primarily these improvements are (1) array feed, (2) better subreflector, and (3) new surface panels set more precisely.

Analytical improvements in the combination of weather statistics with link performance uncertainties have been described by M. A. Koerner [2]. Both frequencies benefit from this improvement in estimated performance.

To be exactly correct, the analysis should contain the effects of tolerances or uncertainties in the link parameters. However, the comparisons are relative and the total uncertainties are similar. Therefore, answers to first order are not affected. This assertion will be tested in later work.

II. Mass, Size, and Transmitter Power Analysis

This analysis does not model all parts of communication system mass, size, and power. It considers only those parts of the system which compete for mass at the expense of some other part in the downlink communications system. That is, we are looking for a mass minimization and not actual total mass.

Items that have a tare mass, such as transponders, support power converters, microwave components, uplink hardware, emergency communications hardware, and so forth, are not considered in the mass analysis.

As a first order analysis, structure is considered to be proportional to the mass of the communication system. It, therefore, does not enter into the mass optimization process outlined here.

The analysis includes the consideration of mounting the transmitter on the antenna either as a separate package on the backside of a parabolic dish or as an integral design included in an array antenna. The mass of the power and the power system, except for the transmitter power converter, are not considered because they are accounted for in the MSR locomotion requirements. For the MSR, the locomotion power requirements exceed that of the downlink which is only required when the rover is at rest. It is only when the raw power for the transmitter exceeds the power available for locomotion that the communication system is constrained.

Primary communications requirements are for 30 kbps telemetry.

A. Parabolic Dish and Lumped Transmitter Mass Analysis

The mass of the spacecraft Telecommunications System consisting of a downlink components parabolic dish, lumped transmitter, heat radiator and transmitter-power converter, for which there are trade-offs, is as follows:

mass = mass of transmitter

+ mass of power converter

+ mass of antenna

+ mass of heat radiator (if separate from antenna)

In equation form this becomes

$$W = K_T P_T + K_A A_T + K_R A_R + K_C \sqrt{P_T/n_T} \qquad (1)$$

where

W = the mass of the downlink system (kg),

P_T = the spacecraft radiated radio-frequency power (watts),

n_T = the efficiency of converting raw direct-current power to radio-frequency power (dimensionless),

A_T = the actual antenna physical area (meter^2),

A_R = the actual spacecraft heat radiator area used to dissipate the heat not radiated by the antenna surface (meter^2),

K_T = the coefficient that relates transmitter radio-frequency power to mass (kg/watt),

K_A = the coefficient that relates actual physical area of the antenna to mass (kg/meter^2),

K_C = the coefficient that relates the converter power to mass (kg/$\sqrt{\text{watt}}$), and

K_R = the coefficient that relates actual physical area of the heat radiator to mass (kg/meter^2).

Equation (1) must be reduced to one independent variable, say P_T, for the analysis. This will be accomplished by relating the variables P_T, A_T, and A_R to one another. Also, other constraints imposed by the application will be defined. The variables P_T and A_T are related to each other by the Riis Equation and the level of performance to be satisfied by the link. Thus, signal power S is given by

$$S = \frac{P_T L_T (A_T \eta_T) G_R L_M L_r L_p}{4\pi R^2} \qquad (2)$$

where

P_T = transmitter power (watts)

L_T = transmitter circuit losses ($0 \leqslant L_T \leqslant 1$)

η_T = transmitter antenna efficiency ($0 \leqslant \eta_T \leqslant 1$)

L_M = data modulation loss, relating data power to total power ($0 \leqslant L_M \leqslant 1$)

G_R = ground receiving antenna gain (dimensionless)

L_p = performance margin for tolerances and weather ($0 \leqslant L_p \leqslant 1$)

L_r = receiving circuit loss ($0 \leqslant L_r \leqslant 1$)

R = range (meters)

Multiplying Eq. (2) by the bit time T_B and dividing by the noise spectial density $N_0 = kT_{sys}$ yields the energy per bit to noise spectral density ratio, a dimensionless quality which together with a channel coding scheme determines system performance. Thus,

$$(ST_B/N_0) = \frac{P_T L_T (A_T \eta_T) G_R L_M L_p T_B}{kT_{sys}\, 4\pi R^2} \tag{3}$$

Other parameters in Eq. (3) are

k = Boltzmann's constant, 1.3806×10^{-23} (joules/kelvin)

T_{sys} = system noise temperature (kelvin)

T_B = bit time = 1/data rate (seconds)

1. Solution for the system mass with respect to the transmitter power. Equation (3) can be solved for the product $P_T A_T$ in terms of the other parameters. Thus,

$$P_T A_T = (ST_B/N_0)\, \frac{kT_{sys}\, 4\pi R^2}{G_R \eta_T L_M L_T T_B L_p} \tag{4}$$

The quantity (ST_B/N_0) is related to channel error rate through a function which depends on the particular channel coding scheme in use. A minimum value of (ST_B/N_0) is therefore required to meet the maximum allowable error rate. Equation (4), therefore, amounts to a constraint on the power-area product.

$$P_T A_T \geqslant B_1 \tag{5}$$

where

$$B_1 = (ST_B/N_0)\, \frac{kT_{sys}\, 4\pi R^2}{G_R \eta_T L_M L_T T_B L_p}$$

The area A_T is being kept explicit, rather than antenna gain, because physical size becomes an important constraint, later. The first two terms of Equation (1) are now expressed in terms of P_T.

$$W = K_T P_T + K_A B_1/P_T + K_R A_R + K_C \sqrt{P_T/n_T} \tag{6}$$

Now, the mass of the heat radiator must be related to transmitter power P_T. In terms of the direct-current to radio-frequency conversion efficiency n_T, the dissipated power is

$$P_D = P_T \left[\frac{1}{n_T} - 1\right] \tag{7}$$

Dissipated power can also be related to the area A_D by thermal characteristics of the radiator. Thus,

$$P_D = \epsilon\, \sigma\, (T_1^4 - T_2^4) A_D \tag{8}$$

where

P_D = thermal power radiated (watts)

A_D = radiating area (meter^2)

T_1 = temperature of the surface A_D (kelvin)

T_2 = effective temperature of surrounding space (kelvin)

ϵ = emissivity of the surface ($0 \leqslant \epsilon \leqslant 1$)

σ = Stefan-Boltzmann constant, 5.6696×10^{-8} (watt/kelvin-meter^2)

The process of equating (7) and (8) and solving for A_D yields

$$A_D = P_T\, \frac{\left[\frac{1}{n_T} - 1\right]}{\epsilon\sigma\,(T_1^4 - T_2^4)} \tag{9}$$

or

$$A_D = P_T B_2 \tag{10}$$

where

$$B_2 = \frac{\left[\frac{1}{n_T} - 1\right]}{\epsilon\sigma\,(T_1^4 - T_2^4)}$$

The total dissipation area A_D is composed of both sides of the transmitting antenna plus an auxiliary area A_r, if $2A_T$ is not sufficient to radiate at the temperatures T_1 and T_2. Thus

$$A_D = A_r + 2A_T \tag{11}$$

or

$$A_r = A_D - 2A_T \tag{12}$$

Using the relationships defined in Eqs. (7) through (12), the mass equation (6) becomes

$$W = K_T P_T + K_A B_1/P_T + K_r (A_D - 2A_T) + K_C \sqrt{P_T/n_T} \quad (13)$$

which becomes

$$W = K_T P_T + (K_A - 2K_r) B_1/P_T + K_r B_2 P_T + K_C \sqrt{P_T/n_T} \quad (14)$$

Rearranging terms yields

$$W = (K_T + B_2 K_r) P_T + (K_A - 2K_r) B_1/P_T + K_C \sqrt{P_T/n_T} \quad (15)$$

with the constraint

$$\begin{aligned} K_r &= 0,\ P_T \leqslant \sqrt{2B_1/B_2} \\ &= K_R,\ \text{otherwise} \end{aligned} \quad (16)$$

Physically, this means the extra radiating area vanishes if not needed.

The power converter for the transmitter is part of the mass trade-off with power. This is found to vary with the square root of the power [3]. The mass function of the power converter W_{pc} becomes

$$W_{pc} = K_C \sqrt{P_T/n_T} \quad (17)$$

where n_T, K_C, and P_T have been previously defined.

2. **Solution of the system mass with respect to the antenna area.** Previously, the mass W had been determined to be (equation (15)):

$$W = (K_T + B_2 K_r) P_T + (K_A - 2K_r) B_1/P_T + K_C \sqrt{P_T/n_T} \quad (18)$$

where the power converter had been included. From the relation (5) previously derived,

$$P_T = B_1/A_T \quad (19)$$

Let us substitute Eq. (19) into Eq. (18) which yields the following:

$$W = (K_T + B_2 K_r) B_1/A_T + (K_A - 2K_r) A_T + K_C \sqrt{B_1/(A_T n_T)} \quad (20)$$

with the constraint

$$A_D \leqslant 2A_T \quad (21)$$

Now if we solve for the constraints in terms of A_T, by using Eqs. (5) and (10),

$$A_D = B_2 P_T \leqslant 2A_T \quad (22)$$

Then we have,

$$A_D = B_1 B_2/A_T \leqslant 2A_T \quad (23)$$

The final constraint is as follows:

$$\begin{aligned} K_r &= 0,\ A_T \geqslant \sqrt{B_1 B_2/2} \\ &= K_R,\ \text{otherwise} \end{aligned} \quad (24)$$

3. **Discussion of parabolic antenna results.** The computational results of the preceding formulas for mass in terms of P_T and A_T are embodied in Figs. 1, 2, 3, 4, and 5. They represent the cases of 34 m and 70 m Deep Space Network (DSN) usage for both 8 GHz and 32 GHz for the typical parameters shown in Table 1.

Figures 1 and 2 are for spacecraft antenna and transmitter mass versus spacecraft transmitter power with the 34 m and 70 m Deep Space Stations, respectively, at 8 GHz and 32 GHz. These curves show a distinct minimum mass as the transmitter mass and antenna mass compete with one another. The 32 GHz band is shown as a definite advantage over 8 GHz with regard to mass.

Constraints of 30 watts of radio-frequency power and 1.57 square meters (1.414 meter diameter for dish antenna equivalent to diagonal dimension of 1.0 square meter flat plate array) were assumed and shown on Figs. 1 and 2. The minimum spacecraft antenna and transmitter masses are all within the 30 watt radio-frequency power constraint.

Figures 3 and 4 are for spacecraft antenna and transmitter mass versus spacecraft antenna area with the 34 m and 70 m stations, respectively, at 8 GHz and 32 GHz. These curves also show a distinct minimum mass as the transmitter mass and antenna mass compete with one another. However, for the 34 m DSN antenna, the minimum mass 8 GHz design is slightly outside of the area constraint.

The minimums of the curves shown in Figs. 1, 2, 3, and 4 are rather broad. As a result only a slight penalty is suffered when the design is slightly off the minimum. Figure 5 shows the requirements for the power-area product for the 34 m and 70 m stations, respectively, for 8 GHz and 32 GHz. The area and power constraints are also shown on this figure.

B. Flat-Plate Array Antenna and Distributed Transmitter Analysis

The flat-plate array differs from the parabolic dish and lumped transmitter combination considerably. One aspect of these differences is that the transmitter is integrated into the antenna surface with each antenna element. That is, one gets an elemental power associated with each elemental area of the array. In essence, one obtains an elemental power-area product for each elemental area. Although the elemental power is adjustable, the mass of the assembly is not a strong function of the radiated radio-frequency power. This makes the analysis and optimization different from the parabolic dish and lumped transmitter case presented before in that there is no obvious power-area trade-off for the flat plate array.

1. Solution of the system mass

a. Area. The area of the array is made up of discrete antenna elements distributed over one surface of the flat plate. These are distributed in a definite pattern which will be assumed to be uniform over a square plate as shown in Fig. 6. A square configuration is not essential and is only used for the convenience of analysis. The elements will also be distributed with a separation related to the wavelength. The separation Λ than is related by:

$$\Lambda = D\,\lambda = D\,c/f \qquad (25)$$

where

- Λ is the separation of the antenna elements (meters),
- D relates the separation of the elements to the wavelength (dimensionless),
- λ is the wavelength (meters),
- c is the velocity of light (meters/second), and
- f is the frequency of the transmitter (hertz).

There are N antenna elements in each row and column for a total of N^2 elements on the flat plate. Each antenna element occupies an area which is related to the following:

$$A_o = (D\lambda)^2 \qquad (26)$$

where A_o is the physical area occupied by each antenna element (meter^2).

The total physical area (one side of the flat plate) then becomes:

$$A_T = N^2 A_o \qquad (27)$$

where A_T is the total one sided physical area of the flat plate (meter^2).

b. Transmitter. The transmitter is distributed in discrete components immediately behind the discrete antennas for low radio-frequency losses. They are thermally part of the array for heat dissipation. Each transmitter is isolated from one another with metal boxes to make their operation as independent as possible. Each is excited from a manifold whose purpose is to distribute radio-frequency power uniformly with a stable phase and amplitude (except in the case of an electronically steerable array). There is also a direct-current power distribution system associated with the transmitter elements. The mass of the boxes for isolation will be considered to be part of the array structure while the manifold and direct-current power distribution system will be considered to be part of the transmitter.

The mass of the transmitter element is depicted as shown in Fig. 7. From this figure, the mass does not reduce below W_o with power P_o because of the tare mass of the manifold and direct-current power distribution system. Therefore, the base power to be considered will be P_o. The radio-frequency output power of the array can be written as:

$$P_T = P_o N^2 \,(2^M)^m \qquad (28)$$

where

- P_o = the element base radio-frequency power (watts),
- P_T = the total radio-frequency power (watts),
- m = 0, 1, 2, . . . , 22 for 8 GHz (dimensionless) (maximum power = 2.5 watts, m = 50),
- m = 0, 1, 2, . . . , 8 for 32 GHz (dimensionless) (maximum power = 0.05 watts, m = 8), and
- M = 1/4 (m, M are selected for computing values of radio-frequency powers and masses in plotting).

c. Power-area product. From the previous two sections, the power-area product becomes:

$$P_T A_T = P_o A_o N^4 \,(2^M)^m \qquad (29)$$

where the terms have already been defined. Now the required power-area product is related by equation (4) which can be written as:

$$P_T A_T = (ST_B/N_0)\ \frac{kT_{sys}\,4\pi R^2}{G_R \eta_T L_M L_T T_B L_P} = B_1 \tag{30}$$

where the terms have already been defined.

d. Total mass. The mass of the flat-plate array system, like equation (1), can be defined as:

mass = mass of flat plate structure

+ mass of transmitter

+ mass of heat radiator (if separate from flat plate array).

Example designs have been performed where the mass of the transmitter has been estimated to be 10% of the total flat plate array mass when the transmitter element power P_o is 0.05 watts. The total mass of the element (kg) including transmitter is

$$W_o = K_A A_o \tag{31}$$

where K_A and A_o have been previously defined. The mass of the flat-plate structure is then

$$W_A = 0.9\, W_o N^2 = 0.9\, K_A A_o N^2 \tag{32}$$

The mass of the transmitter becomes

$$W_T = 0.1\, W_o N^2\, 10^{0.01574m} = 0.1\, K_A A_o N^2\, 10^{0.01574m} \tag{33}$$

where

W_A = the mass of the flat plate structure or flat plate without the transmitter (kg)

W_T = the mass of the transmitter (kg)

The factor

$$10^{0.01574m} \tag{34}$$

accounts for the compounding effect of the transmitter mass increase of 15% with every doubling of radio-frequency power.

The mass of the radiator was previously defined as

$$W_R = K_r (A_D - 2A_T) \tag{35}$$

where

$$\begin{aligned} K_r &= 0, \text{ if } A_D \leqslant 2A_T \\ &= K_R, \text{ otherwise} \end{aligned} \tag{36}$$

and

$$A_D = P_T\ \frac{\left[\frac{1}{n_T} - 1\right]}{\epsilon\sigma\,(T_1^4 - T_2^4)} = P_T B_2 \tag{37}$$

By making the appropriate substitutions,

$$W_R = K_r\,[P_o N^2 (2^M)^m B_2 - 2A_o N^2] \tag{38}$$

so that the total mass is

$$W = 0.9\, K_A A_T + 0.1\, K_A A_T \cdot 10^{0.01574m}$$

$$+ K_r\,[P_o N^2\,(2^M)^m B_2 - 2A_T] + K_C \left[\frac{P_o N^2\,(2^M)^m}{n_T}\right]^{1/2} \tag{39}$$

with the constraint

$$\begin{aligned} K_r &= 0, \text{if } P_o N^2\,(2^M)^m B_2 \leqslant 2A_t \\ &= K_R, \text{ otherwise} \end{aligned} \tag{40}$$

2. Power-area requirement. The minimization of the flat-plate array does not occur in the same way as it does in the parabolic dish case. There is no choice of area versus power as in the case of the parabolic dish. Power and area are directly coupled. The choice that the designer has at his disposal is in the selection of the number of elemenets or possibly the power output of each element, P_o.

To show the minimization on the cuves that will result from the analysis, it is essential to compute and draw the power-area requirement to meet the system performance. This is B_1 as shown in a previous section.

3. Discussion of flat-plate array results. The computational results of the preceding formulas for the flat-plate array are embodied in Figs. 8 and 9. They represent the cases of 34 m and 70 m DSN usage for both 8 GHz and 32 GHz for the indicated parameters.

Figure 8 is for spacecraft antenna and transmitter mass versus spacecraft power-area product at 8 GHz and 32 GHz. The number of elements across the side of the flat plate, N, is used as a parameter as well as the power X area requirements B_1 of equation (5). On the left hand side of this curve the shape is determined largely by the power converter. On the right hand side, the shape for the 8 GHz curves are determined largely by the flat-plate array mass while the 32 GHz curves are determined by a combination of the flat-plate array mass and the heat radiator. The heat radiator is more of an effect for the 32 GHz case because the size of the elements are sixteen times smaller for the same number of elements, N. This effect did not show for 8 GHz even though the 8 GHz element was capable of about ten times the power of the 32 GHz element.

Examining the curves on Fig. 8, the 34 m performance requirement curve intersects the 8 GHz spacecraft antenna-transmitter mass curves for the number of elements 7 through 15. The mass is monotonically increasing with the number of elements, N. The minimum mass occurs for $N = 7$ (minimum on the boundary). An examination of the curves for 32 GHz shows that the 70 m performance requirement case intersects the 32 GHz spacecraft antenna-transmitter mass curves with the number of elements 10 through 13. Because of the peculiar way the power converter and heat radiator combine, the mass generally decreases with the number of elements, N. In some cases the mass can actually show a minimum as a function of the number of elements, N. This effect is more pronounced in studies without the power converter mass added (not shown).

Figure 9 shows the spacecraft array RF power versus spacecraft array area with the number of elements, N, and power-area product requirements for both the 34 m and 70 m DSN usages and 8 GHz and 32 GHz. Also shown are the assumed constraints of 1 square meter (1.4 meter diagonally) for the antenna area and 30 watts for the radio-frequency power. This allows one to determine if the minimum mass can be achieved for the number of elements mentioned above. For instance, this curve shows that the minimum mass with the number of elements of 7 for the 8 GHz 34 m, cannot be achieved because 9 must be used due to the power constraint.

An examination of the curves for the flat-plate array, compared to the parabolic dish, shows that 32 GHz has a decided mass advantage over 8 GHz.

III. Discussion of Parameters

A. Transmitters and Power Supplies

In general, redundant transmitters are required with the exception of the distributed ones such as that used in the flat-plate array which has inherent redundancy. For this reason, the mass of the transmitters such as traveling-wave tubes and solid-state amplifiers are doubled.

The switching mechanisms of complicated power supplies such as used on traveling-wave tube amplifiers are built with their individual power supplies and are therefore also doubled. Solid-state RF amplifiers will likely have their own power supplies also.

Distributed arrays (power amplifiers-antenna elements) have a certain amount of effective redundancy built into the system so that failure of one or several transmitting elements only partially degrades the output of the array. For this reason, the distributed power amplifier is not doubled for redundancy. The power converter for the array, however, can fail. Rather than having the power switched between redundant power converters, the power would be derived from split power converters, each serving half of the distributed power amplifiers. That is, a single power converter failure only causes roughly three decibels degradation in the communication link.

Since the mass of the power converter is a function of the square root of the delivered power, the mass of the split power converters increases by the square root of two over a single power converter.

The coefficient to convert power-converter output to mass is derived from the Mars Sample Return Technology Study. This data is consistent with [3] which is 0.38 kg/$\sqrt{\text{watt}}$. This article assumes that this coefficient includes the power-converter packaging. It also assumes that the power converter is mounted on the body of the Mars Sample Return for purposes of heat dissipation and requires no special heat radiator. Power from the power converter is wired across gimbals for the radio-frequency power amplifiers.

The coefficient to convert radio-frequency power output to transmitter mass has been derived. For traveling-wave tube amplifiers, this number is 0.434 kg/watt. For the distributed amplifier coefficient, see the discussion in Section II. This was related to the mass of the flat-plate array itself.

The mass for the distributed power amplifiers for the flat plate array, as shown in the analysis, is rather insensitive to the power output. The primary cause for this is the assumption by G. Klein[1] that the structure for the radio-frequency amplifiers, antenna elements, manifolds and heat conduction mass

[1] G. Klein, Planetary Spacecraft Systems Technology, Final Report 1986, JPL D-3731 (internal document), Jet Propulsion Laboratory, Pasadena, Calif., 1986.

had a density of 0.25 of that of a solid billet of aluminum. This makes the mass much larger than subsequent estimates by L. Riley [4].

B. Antennas

The mass of parabolic antennas was based on the Viking (V075) graphite-epoxy honeycomb dishes. It was assumed that the only mass variable of choice was that of the dish area. That is, the feed was about the same mass for antenna size or frequency. Area efficiencies assumed for the parabolic dish were 55% for both 8 GHz and 32 GHz.

The flat-plate array mass has been discussed in the section above. The flat-plate array design assumed elements with a separation of Λ. This separation will cause lobing of the antenna pattern. It has been assumed that this can be overcome by breaking each element into subelements with a net power of a single element. Area efficiencies for the flat-plate array are assumed to be 0.9 at all frequencies.

IV. Summary

Within the constraints and parameters assumed, a viable design can be made to perform the telecommunications part of the Mars Sample Return Mission at either 8 GHz or 32 GHz. Under these circumstances, the mass, power and size show a definite advantage of roughly 2:1 of using the 32 GHz over 8 GHz as shown in Table 2.

In the designs shown above, there is no advantage of mass for the parabolic antenna versus the flat-plate array for a fixed frequency. It is believed that a much lighter design for the flat plate can be made than the example one chosen here and will show an advantage in mass in the future. The flat plate example design does show a definite advantage of size.

Acknowledgment

The author wishes to express appreciation to R. L. Horttor and P. W. Kinman for critiquing the article before submission.

References

[1] W. A. Imbriale, A. M. Bhanji, S. Blank, V. B. Lobb, R. Levy, and S. Rocci, "Ka-band (32 GHz) Performance of 70-Meter Antennas in the Deep Space Network," *TDA Progress Report 42-88*, vol. October-December 1986, Jet Propulsion Laboratory, Pasadena, California, pp. 126-134, February 15, 1987.

[2] M. A. Koerner, "Relative Performance of X-band and 32 GHz Telemetry Links on the Basis of Total Data Return Per Pass," *TDA Progress Report 42-87*, vol. July-September, 1986, Jet Propulsion Laboratory, Pasadena, California, pp. 65-80, November 15, 1986.

[3] J. Leisenring, "Study and Analysis of Satellite Power Systems Configurations for Maximum Utilization of Power," *NASA Report CR-898*, TRW Systems, Redondo Beach, Calif., for Goddard Space Flight Center, October, 1967.

[4] A. L. Riley, "Ka-Band (32 GHz) Spacecraft Development Plan," *TDA Progress Report 42-88*, vol. October-December, 1986, Jet Propulsion Laboratory, Pasadena, Calif., pp. 164-173 February 15, 1987.

Table 1. Typical parameters used for results

Parameters	X-Band	Ka-Band
DSN		
Canberra, Improved 34 m		
Antenna Gain, dB	67.62	78.57
System Noise Temperature, K	24.98	31.2
Canberra, Improved 70 m		
Antenna Gain, dB	73.89	84.84
System Noise Temperature, K	24.98	31.2
Frequency, GHz	8.450	32.0
Elevation Angle, deg	30	30
SYSTEM		
Range, AU	2.683	2.683
Bit Rate, bps	30000	30000
ST/N_0, dB	4	4
Circuit and Polarization Losses, dB	-0.86	-0.92
Performance Margin, dB	-1.15	-3.55
Link Reliability, %	90	90
SPACECRAFT		
VO 75 Parabolic Dish, Heat Radiator; Redundant TWTAs and Power Converters		
Antenna Area Efficiency	0.55	0.55
Antenna Area to Weight, kg/m^2	2.94	2.94
Transmitter Power to Weight, kg/Watt	0.434	0.434
Radiator Area to Weight, kg/m^2	20.77	20.77
Power Converter Power to Weight, kg/Watt$^{0.5}$	0.76	0.76
Flat Plate Array/Transmitter, Heat Radiator; Split Power Converter		
Antenna Area Efficiency	0.9	0.9
Modulation Loss Factor	0.9698	0.9698
Antenna Area to Weight, kg/m^2	25.7	25.7
Radiator Area to Weight, kg/m^2	20.77	20.77
Power Converter Power to Weight, kg/Watt$^{0.5}$	0.537	0.537
Emissivity, %	75	75
Antenna Temperature, K	380	380
Surrounding Temperature, K	260	260
Modulation Loss Factor	0.9698	0.9698

Table 2. Optimum design analysis results

	34m						70 m					
	8 GHZ			32 GHz			8 GHz			32 GHz		
	W	m^2	*kg*	*W*	m^2	*kg*	*W*	m^2	*kg*	*W*	m^2	*kg*
Parabola	13	1.6**	17	5.8	0.89	8.8	6.8	1.0	8.8	2.9	0.4	5.8
Flat Plate	30*	0.4	26	20	0.11	8.0	30	0.11	11	13	0.06	5.4
No. of Elements		902			1802			502			13	

*Power constrained design
**Area (envelope) constrained design

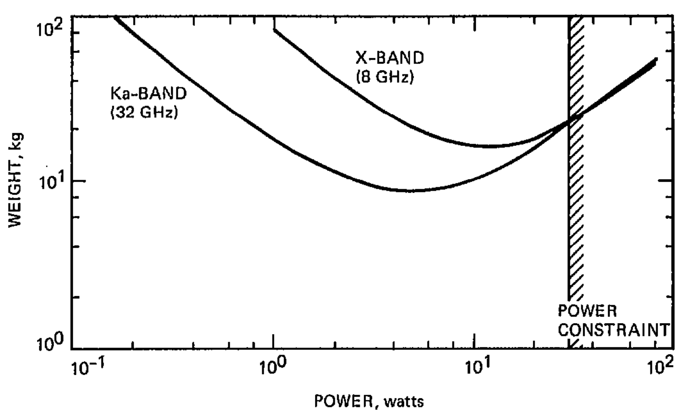

Fig. 1. The weight of the spacecraft's parabolic antenna and transmitter vs its transmitter RF power for 8 and 32 GHz using the Canberra improved 34-m antenna

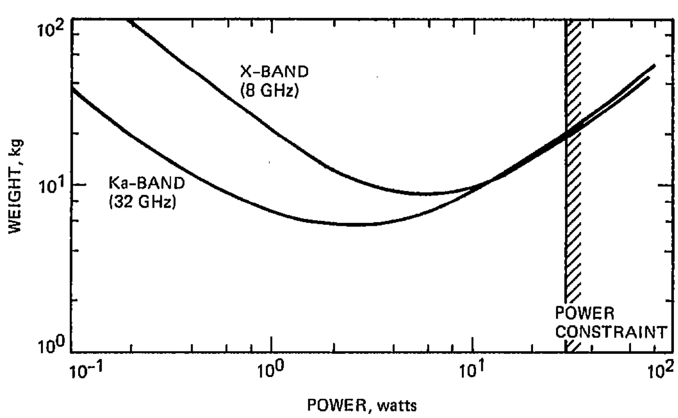

Fig. 2. The weight of the spacecraft's parabolic antenna and transmitter vs its transmitter RF power for 8 and 32 GHz using the Canberra improved 70-m antenna

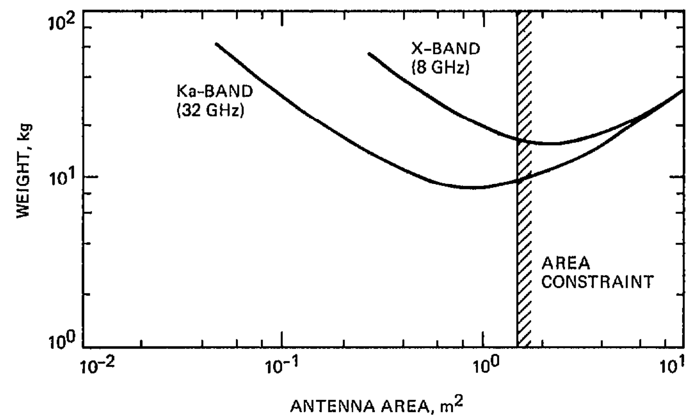

Fig. 3. The weight of the spacecraft's parabolic antenna and transmitter vs the antenna area for 8 and 32 GHz using the Canberra improved 34-m antenna

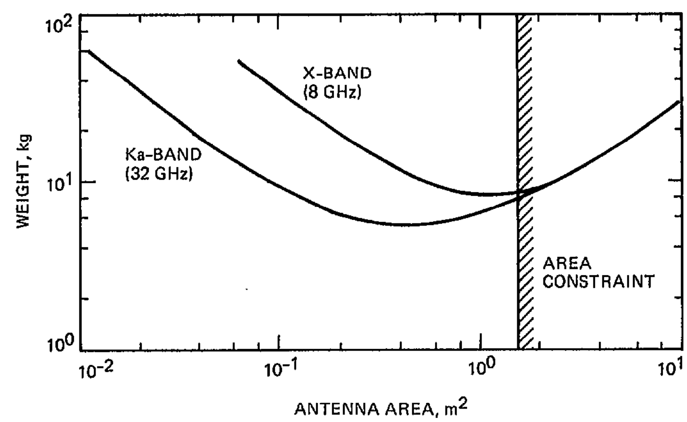

Fig. 4. The weight of the spacecarft's parabolic antenna and transmitter vs the antenna area for 8 and 32 GHz using the Canberra improved 70-m antenna

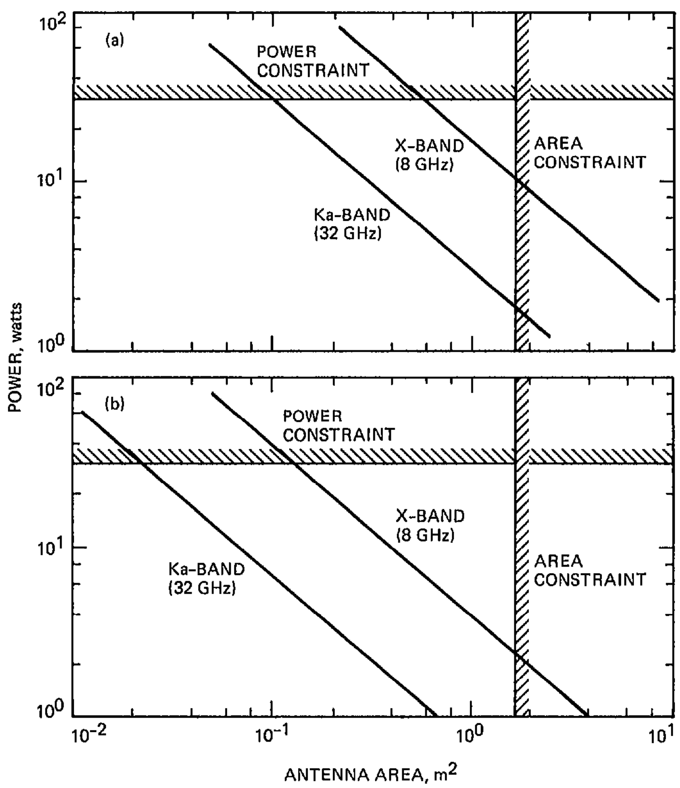

Fig. 5. The required spacecraft parabolic antenna RF power-area product vs RF transmitter power and antenna area for 8 and 32 GHz: (a) Canberra improved 34-m antenna and (b) Canberra improved 70-m antenna

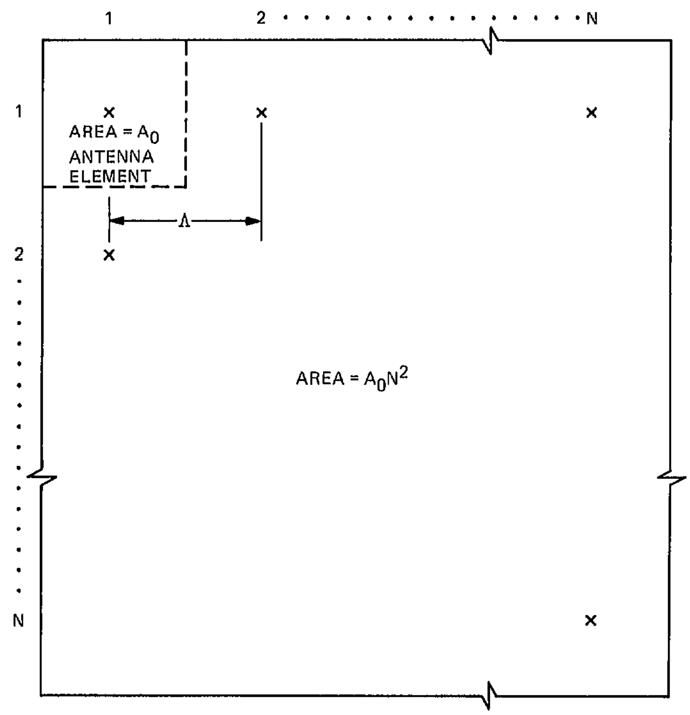

Fig. 6. Flat-plate array layout

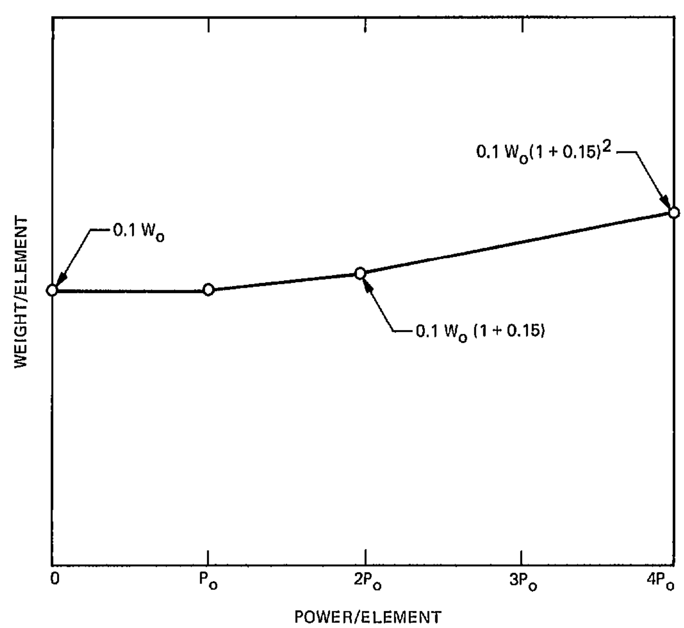

Fig. 7. Weight vs power for the flat-plate array

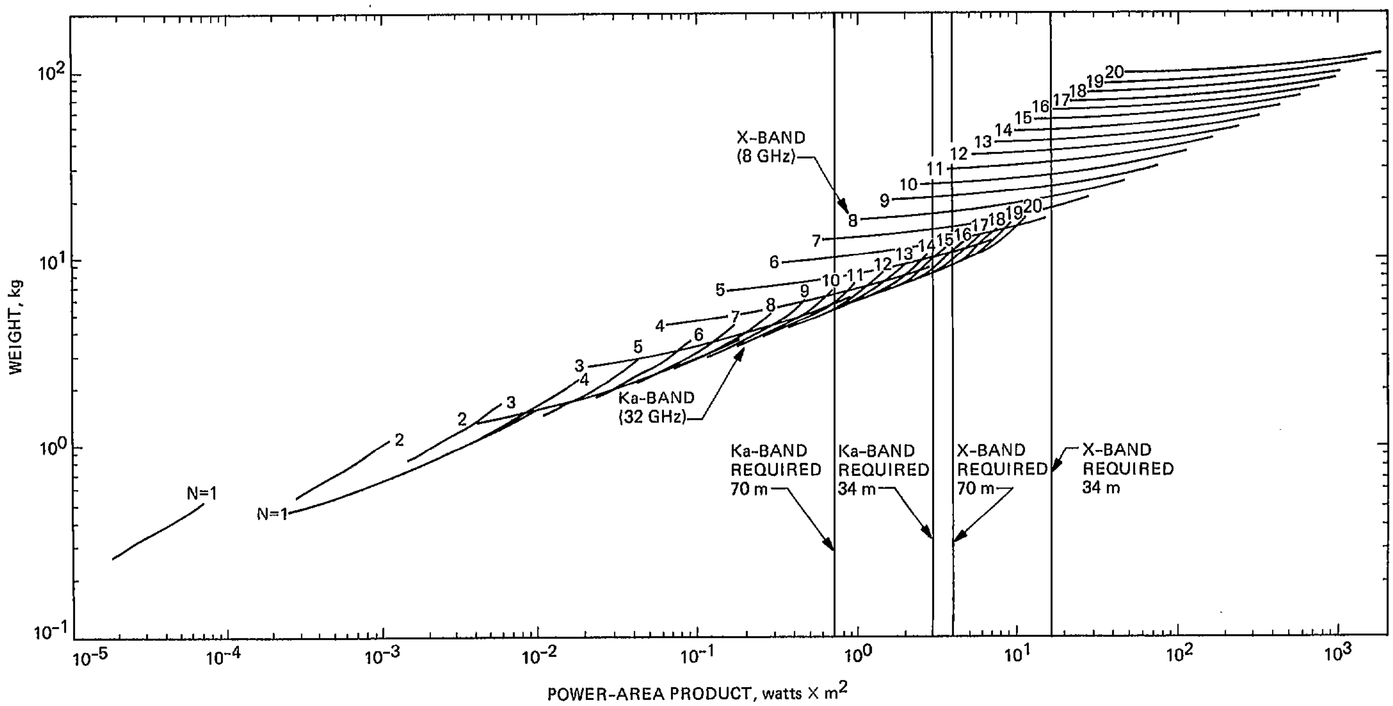

Fig. 8. The flat-plate array weight vs power-area product

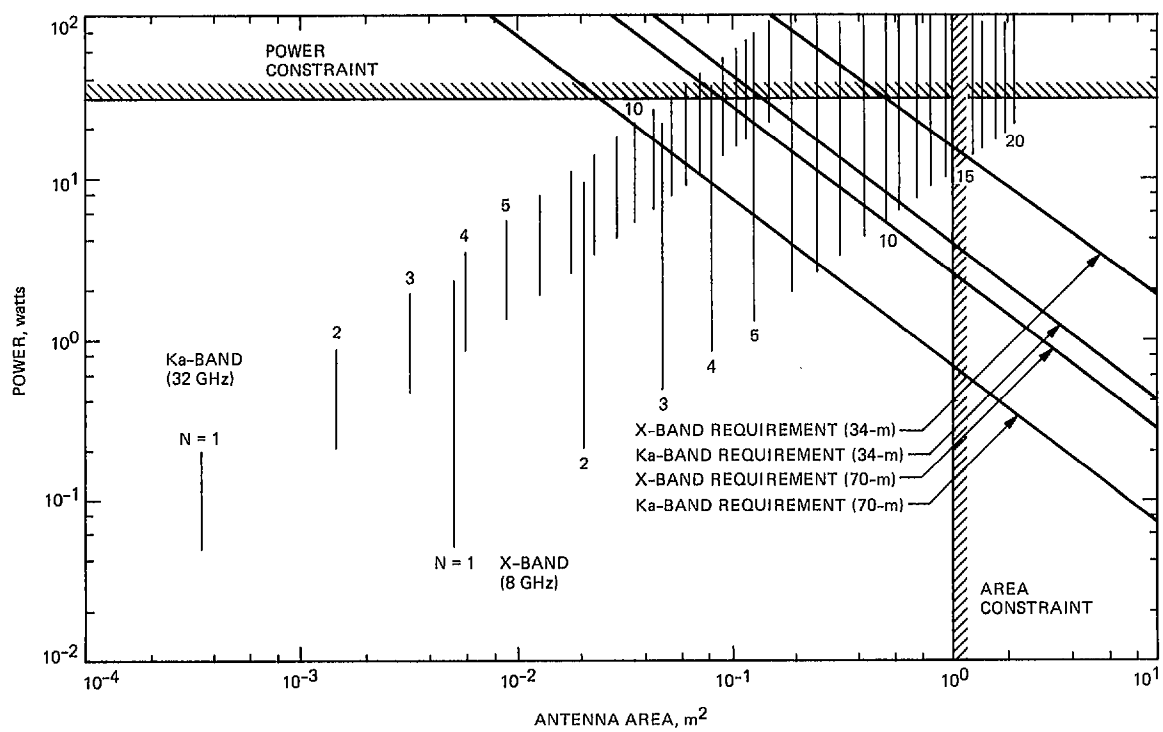

Fig. 9. The required and available flat-plate array RF power area product vs RF transmitter power and antenna area for 8 and 32 GHz, number *N*, and Canberra improved 34- and 70-m antennas